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REDUCTION OF NO_X EMISSIONS FROM AUTOMATED BOILERS BY MULTIPLE AIR STAGING

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ABSTRACT: Within recent years the utilisation of „new“ biomass fuels (e.g. agricultural residues and energy crops) in biomass combustion processes has gained relevance. Unfortunately, most of these new biomass fuels are characterised by elevated contents of i.e. N resulting in higher NO_x emissions. Currently available biomass heating systems for the combustion of non-wood biomass fuels have a high system complexity and cost intensive secondary measures have often to be applied. Thus, emission reduction by primary measures can be a meaningful and economically attractive solution for the development and design of biomass combustion systems. In order to investigate the influence of multiple air staging on NO_x emissions, test run series with different biomass fuels have been performed at a pilot-scale biomass combustion plant specially designed for the application of multiple air staging. The experimental investigations were accompanied and supported by CFD simulations in order to gain more detailed information regarding NO_x formation. The results show that the potential to reduce NO_x emissions by multiple air staging is considerable (up to 50% lower NO_x emissions compared to Austrian emission limits achievable). Thus, NO_x reduction by multiple air staging is of relevance for the development and design of Low-NO_x combustion technologies. The application of multiple air staging may provide a cost attractive alternative to secondary measures and thereby contributes to a significant widening of the feedstock potential for heat and power production from biomass and the reduction of NO_x, which is a primary contributor to photochemical smog.

Keywords: agricultural residues, NO_x emission, air staging, primary measures

1 INTRODUCTION AND OBJECTIVES

Within recent years the utilisation of „new“ biomass fuels (e.g. agricultural residues and energy crops) in biomass combustion processes has gained relevance. Unfortunately, most of these new biomass fuels are characterised by elevated contents of N, S, Cl as well as ash forming elements. Consequently, compared with the combustion of chemically untreated wood fuels, higher NO_x-, HCl- and SO_2-emissions as well as more severe ash related problems (aerosol formation, deposit formation, corrosion, slagging) must be expected. NO_x emissions from biomass combustion are mainly formed from the nitrogen that is contained in the fuel and depends on the operational conditions during combustion. Thermal and prompt NO_x formation is almost negligible [1, 2].

Currently available biomass heating systems for the combustion of non-wood biomass fuels show a high system complexity and cost intensive secondary measures have often to be applied to keep strict emission limits. Previous studies which summarize and evaluate data available regarding the influence of air staging on NO_x and PM_1 emissions for fixed-bed biomass combustion have shown that proper air staging is a meaningful measure for NO_x reduction [3, 4, 5, 6]. Air-staging means that the combustion air is introduced into different zones of the combustion chamber. In modern biomass furnaces the combustion chamber is usually separated into a reduction zone where devolatilisation and an oxidizing zone where complete burnout of the flue gas takes place. Advanced air staging means that air staging takes place under well-defined conditions and in a controlled way and that also flue gas recirculation is considered in the overall concept. According to [6, 7, 8] 30 to 70% NO_x reduction can be achieved by air staging. Thus, emission reduction by air staging (primary measures) can be a meaningful and economically attractive solution for the development and design of biomass combustion systems.

The scope of this work is the investigation of a newly developed 400 kW biomass combustion technology with multiple air-staging with respect to NO_x emissions as well as the related conversion mechanism of the fuel-bound N by means of test runs as well as CFD (Computational Fluid Dynamics) simulations. Multiple air staging means that the combustion takes place staged in different zones (in sum in 4 different reaction zones) of the combustion plant under well-defined conditions and also recirculated flue gas is considered (see Figure 1). The experimental investigations were accompanied and supported by CFD simulations in order to gain more detailed information regarding NO_x formation and to reduce the number of test runs needed. The overall aim was to achieve a fuel flexible and low NO_x operation without the need of additional secondary measures (e.g. SNCR) or at least with considerably reduced efforts regarding secondary measures (less additive consumption). Thus, the understanding of the relevant influencing parameters on NO_x formation (e.g. temperature, residence time and variations in air staging) is of great relevance for a low NO_x combustion of non-wood biomass fuels.

2 METHODOLOGY

In order to investigate the influence of multiple air staging on NO_x emissions, test run series with different biomass fuels (sunflower husk, miscanhtus, wheat straw and hardwood) have been performed at a newly developed 400 kW biomass combustion plant specially designed for the application of multiple air staging. The experimental investigations were accompanied and supported by CFD (Computational Fluid Dynamics) simulations.

2.1 Testing plant

A scheme of the testing plant with a thermal capacity of 400 kW is shown in Figure 1. The plant is equipped with a screw feeder, a horizontally moving grate, a fuel bed section coupled to the gas burner with separately controllable combustion air and recirculated flue gas supplies. Multiple air staging is applied in order to efficiently reduce NO_x emissions in the flue gas. The primary combustion chamber is geometrically separated from the main combustion chamber. Primary air and recirculated flue gas are supplied to the primary combustion zone below the grate. The main combustion chamber (gas burner) is separated into two different reaction zones, a reducing (secondary combustion zone) and an oxidising zone (tertiary combustion zone). Secondary air 1 and 2 (reducing zone) as well as tertiary air (oxidising zone) are injected through radial air nozzles in order to provide efficient mixing of the unburned flue gas with the combustion air for a complete burnout. Furthermore, recirculated flue gas for temperature control is injected in the reducing zone of the combustion chamber. A selected set of test runs per fuel was performed in order to evaluate different influencing parameters.

The cylindrical combustion chamber is surrounded by the radiant boiler section. Downstream the combustion chamber the convective section of the warm water boiler is located.

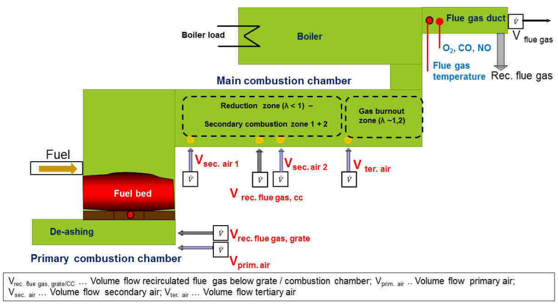

Figure 1: Scheme of the testing plant and the measurement set-up for test runs

The control system of the testing plant is based on combined load and combustion control. Load control is provided by regulation of the primary air and the fuel feed. Combustion control is achieved by the regulation of secondary and tertiary air feeds guided by the O_2 concentration in the flue gas (lambda sensor). The ratio between secondary and tertiary air can be chosen. Flue gas recirculation in the combustion chamber is controlled in dependence of the combustion chamber temperature. Therefore, all air and flue gas flow rates are controlled by means of automatic valves.

2.2 Measurement and analyses methods applied

A significant number of different measurement and sampling technologies was applied in order to accurately evaluate the testing plant as well as to investigate the NO_x emissions (see Figure 1).

To define the performance of the plant, characteristic process data such as air flow rates, temperatures in the different combustion zones and boiler loads were recorded continuously. The combustion air flows have been measured with hot wire anemometers (Type: Bosch HFM-5) and the amounts of recirculated flue gas and the flue gas downstream the boiler have been measured with Prandtl tubes. Moreover, the composition of the flue gas at boiler outlet was continuously measured by using standard flue gas analysers for O_2 (paramagnetic sensor), CO and NO (NDIR) and the different fuels used have been analysed regarding their chemical composition with special focus on N. Moreover, the release of the NO_x precursors (NH_3, HCN, NO, NO_2) during conversion in the gas phase for the fuels investigated has been measured in lab-reactors and was considered for CFD simulations [9]. The moisture content of fuel samples has been determined according to ÖNORM EN ISO 18134-1: 2015 12 15 (determination of the weight loss during drying at 105°C until a constant weight is reached). The ash content has been determined according to ÖNORM EN ISO 18122: 2016 02 15 by determination of the loss of ignition at 550°C. C, H and N contents have been analyzed according to ÖNORM EN ISO 16948: 2015 07 15 (combustion and subsequent gas-phase chromatographical separation and measurement in an elemental analyser).

2.3 Performance of test runs

Comprehensive test runs with accompanying measurements and analyses have been performed at the testing plant in order to investigate the NO_x emissions. Test runs at nominal, at medium (50% nominal load) and at partial load (25%) have been performed with wood chips and with selected agricultural fuels. Particularly, the following fuels have been tested:

- conventional hardwood chips
- miscanthus pellets
- straw pellets with 4 wt.% kaolin
- sunflower husk pellets

Within the scope of the test runs performed the following parameters influencing the NO_x emissions have been investigated:

- Air ratio in the secondary combustion zone 1
- Air ratio in the secondary combustion zone 2
- Load

The air ratio in secondary combustion zone 1 (SCZ 1) is defined as the ratio of the amount of oxidising agents supplied into SCZ 1 (induced by primary air, flue gas recirculation below grate and secondary air 1) divided through the amount of oxidising agents needed for stoichiometric combustion. The air ratio in the secondary combustion zone 2 (SCZ 2) is defined as the ratio of the amount of oxidising agents supplied into SCZ 2 (induced by primary air, flue gas recirculation below grate, secondary air 1 and 2 and flue gas recirculation in SCZ) divided through the amount of oxidising agents needed for stoichiometric combustion. The air ratio in the fuel bed is defined as the ratio of the amount of oxidising agents supplied into the fuel bed (primary air supply and flue gas recirculation below grate) divided through the amount of oxidising agents needed for stoichiometric combustion and the total air ratio is defined as the ratio of the supplied amount of oxidising agents with the total combustion air (primary, secondary and tertiary air supply) divided through the amount of oxidising agents needed for stoichiometric combustion. The total air ratio was kept almost constant during the test runs (total air ratio = 1.2 – 1.25).

In a first test series the influence of the air ratio in SCZ 1 has been evaluated with a constant air ratio in SCZ 2 and a constant boiler load of 200 kW (medium load). In a second test series the influence of the air ratio in SCZ 2 has been evaluated with a constant air ratio in SCZ 1 and a constant boiler load of 200 kW. For the next test series different operating conditions influencing NO_x emissions have been adjusted (temperature in the combustion chamber and load). The different test series have been performed with all 4 fuels selected.

During the test runs the amount of primary air, flue gas recirculation and fuel feed were automatically controlled by the standard control system of the plant. Secondary air 1 and 2 were manually adjusted to the side constraints of the specific test run. The side constraints for all test runs performed have been determined with an in-house developed calculation program before the test runs started. This program calculates the needed amounts of primary combustion air, secondary combustion air 1 and 2 and tertiary air as well as flue gas recirculation on the basis of mass and energy balances for a defined combustion condition (defined air ratio in the SCZ, boiler load and total air ratio). The plausibility of the calculation has been checked by comparing calculated with measured data. In this respect also the amount of false air (difference between calculated and measured combustion air) has been evaluated as false air cannot be controlled and may lead to wrong set-point values for an optimized air staging. During the test runs performed the average false air input could be kept very low and amounted to max. 5% (related to the total combustion air input).

2.4 CFD simulations

The experimental investigations were accompanied and supported by CFD simulations in order to gain more detailed information regarding NO_x formation and to reduce the number of test runs needed.

In order to carry out the CFD simulations considering the NO_x formation a special code considering the conversion of the tars released from the fuel bed has been developed and applied [9]. BIOS developed a tar conversion model for the simulation of gas burners. For that purpose the CFD gas phase model was extended by N-rich and a N-free tar species as well as by a thermal decomposition reaction and a partial oxidation reaction for each tar species. The differentiation between N-rich and N-free species is especially important for a following simulation of the formation of NO_x. The composition and amount of the tar species is either fitted to data from analyses and measurements or determined based on detailed bed simulations in combination with elemental balancing and analysis. Moreover, an in-house developed CFD code regarding NO_x formation has been applied in order to optimise the burner geometry and air staging strategies regarding Low-NO_x operation [2]. Table I gives an overview over the CFD models considered.

Table I: Overview over CFD models applied

	model
Fixed bed combustion	Empirical in-house model [10]
Turbulence	Realizable k-ε- Model
Gas phase combustion	Eddy Dissipation Mode global methane 3-step mechanism (CH_4, CO, CO_2, H_2, H_2O und O_2)
Radiation	Discrete Ordinates Model
Shell-conduction model	3D - heat conduction in the metal sheet surrounding the combustion zone
Tar conversion model	Extension of the gas-phase-model with nitrogen-free and nitrogen containing tars, each with oxidation and thermal decomposition reactions [9]
NO_x formation model	Eddy Dissipation Concept (EDC) / "Skeletal Kilpinen97" reaction mechanism (28 species, 104 reactions) - Calculation of NO_x formation in post-processing based on gas phase combustion simulation with EDC [2]

3 RESULTS

In this section the results of the measurements performed with the testing plant as well as selected results of the CFD simulations performed are summarised.

All test runs and measurements have been performed under stationary conditions of the testing plant. With each fuel representative constant load operation tests were performed. The test runs should provide data and experiences regarding the influence of air staging and different loads on the NO_x emissions.

3.1 Fuel analysis

Table II shows the composition of the fuels tested. The N content of the agricultural fuels varied between 0.28 and 0.79 wt% (d.b.) which are on typical values for agricultural crops and significantly higher than for wood fuels (the N content of the hardwood chips with bark amounted to 0.14 wt% d.b.).

Due to the high N content of sunflower husks and wheat straw it is of great importance to operate a combustion plant under optimal air staging conditions to keep NO_x emissions at a low level as NO_x emissions increase with the N content of the fuel (see Figure 5). The GCVs of the fuels are in a comparable range, somewhat lower for wheat straw due to the high ash content.

Agricultural fuels typically have a low moisture content (<10 wt% w.b.) which leads to high combustion temperatures. Therefore, flue gas recirculation and furnace wall cooling are needed in order to keep the temperature in the combustion chamber in an acceptable range. Wheat straw has been additivated with kaolin (4 wt.% additive related to dry fuel) in order to increase the ash melting temperatures and to reduce the K-release.

3.2 Results of test runs performed with the testing plant

For all fuels tested operation at stable load conditions could be achieved. In Figure 2 the emissions trends regarding CO and NO_x as well as the trends regarding load and relevant temperatures for miscanthus pellets as fuel are presented. Regarding a correct assessment of NO_x emissions a complete burnout is important since NO_x emissions are affected by the burnout quality. The burnout quality is influenced by the furnace technology and by the total air ratio. An important indicator for the burnout quality are the CO emissions. Consequently, the dependency of the CO emissions on the total air ratio has been determined for full and part load. In general, the testing plant showed a very stable operating behavior for all fuels tested indicated by a high burnout quality of the flue gases and by very low CO emissions.

Table II: Chemical compositions of fuels tested
Explanations: w.b. … wet basis; d.b. … dry basis; GCV … gross calorific value

		Miscanthus pellets	Sunflower husk pellets	Wheat straw pellets + 4 wt.% kaolin	Wood chips (hard wood)
moisture	wt% w.b.	8.5	10.5	9.7	18.6
ash content	wt% d.b.	2.6	3.6	9.5	1.5
GCV	kJ/kg d.b.	19.3	20.3	17.7	19.8
C	wt% d.b.	48.0	50.1	44.0	49.5
H	wt% d.b.	6.0	5.9	5.7	5.9
N	wt% d.b.	0.28	0.79	0.69	0.14

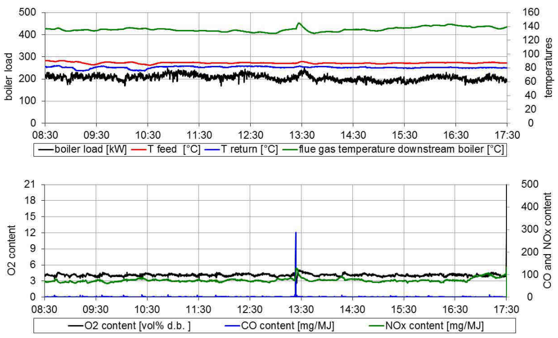

Figure 2: Trends regarding load as well as O_2, CO and NO_x contents in the flue gas during a test run with miscanthus pellets
Explanations: emissions related to the NCV of the fuel

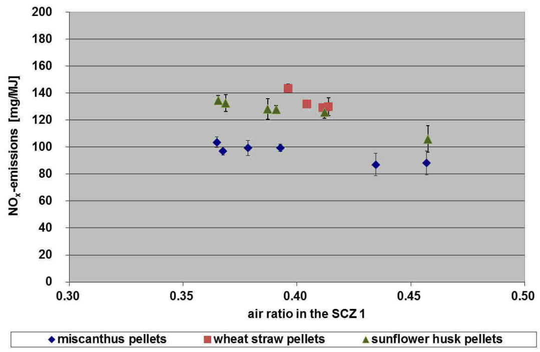

Figure 3: Air ratio in SCZ 1 versus NO_x emissions for constant loads
Explanations: emissions related to related of NCV of the fuel; boiler load: 200 kW; λ_{SCZ2} = 0.8-0.9; total air ratio = 1.2

The average CO emissions amounted to values below 5 mg/MJ (related to the NCV of the fuel). The oxygen content of the flue gas was on average 3.5 vol% (d.b.). Therefore, it can be concluded that constant operation at very good burnout conditions of the flue gas could be achieved. A good burnout quality could be reached for all fuels tested resulting in very low average CO (< 10 mg/MJ, related to NCV of the fuel) at a total excess air ratio of 1.2-1.3 for all load ranges tested.

Figure 3 and Figure 4 show the influence of the air ratio in the secondary combustion zone (SCZ 1 and 2) on NO_x emissions for medium load operation. The results show that the air ratio in the SCZ has a strong influence on NO_x emissions. An optimum can be observed at an air ratio in the SCZ 1 between 0.4 and 0.45 and at an air ratio in the SCZ 2 between 0.8 and 0.9. The highest NO_x emissions have been observed at low air ratios in the SCZ 1 (< 0.4) and in the SCZ 2 (< 0.8). The strongest dependence on NO_x emissions in the flue gas is given by the air ratio in SCZ 1. This can probably be attributed to the increasing flue gas temperatures with increasing air ratios in the SCZ resulting in a faster cracking of the N containing tars into NO_x precursors and therefore a longer residence time for NO_x reduction under reducing conditions (see chapter 3.3).

Figure 5 shows the influence of the load on NO_x emissions. The results show that NO_x emissions at partial load are considerably lower than at full load.

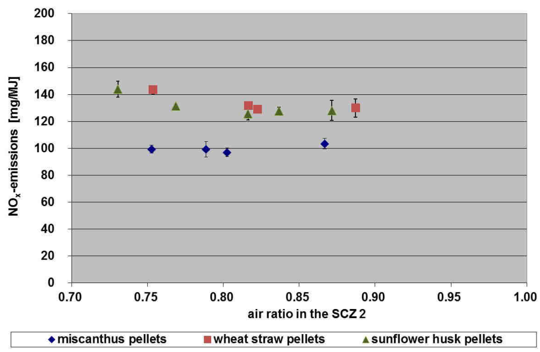

Figure 4: Air ratio in SCZ 2 versus NO_x emissions for constant loads
Explanations: emissions related to the NCV of the fuel; boiler load: 200 kW; λ_{SCZ1} = 0.35-0.42; total air ratio = 1.2

This can probably be attributed to different residence times and temperatures of the flue gas in the reducing zone of the combustion chamber as the reduction of the nitrogenous species to N_2 is a function of residence time and temperature [2]. Thus, increasing residence time decreases NO_x emissions, which is in line with previous studies which also confirm these findings [3, 4, 5].

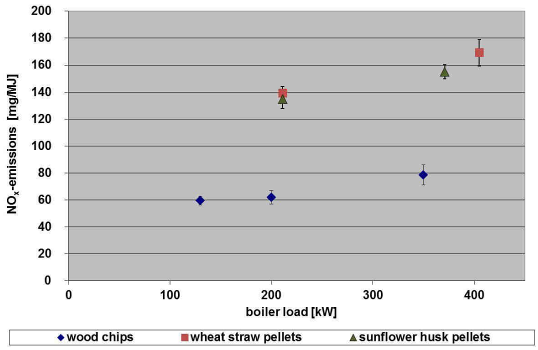

Figure 5: NO_x emissions for varying load conditions
Explanations: emissions related to the NCV of the fuel; λ_{SCZ1} = 0.4; λ_{SCZ2} = 0.8; total air ratio = 1.2-1.25

Figure 6 shows the NO_x reduction potential by applying an efficient multiple air-staging concept. The figure clearly indicates that NO_x emissions increase with increasing N content in the fuel. Consequently, an efficient air staging concept has rising importance for biomass fuels with elevated N contents. Figure 5 also shows the variation of NO_x emissions measured during the test runs performed and demonstrates that low NO_x emissions are also achievable for fuels with elevated N contents by an efficient application of primary measures. The results show that the potential to reduce NO_x emissions by primary measures is considerable as NO_x emissions varied e.g. for sunflower husk pellets between 106 and 169 mg/MJ (related to the NCV of the fuel).

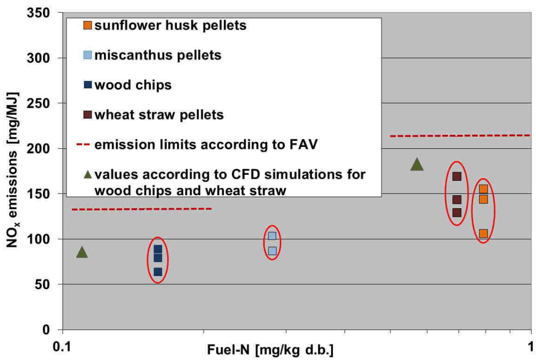

Figure 6: NO_x emissions of fuels tested in dependence of the N content in the fuel
Explanations: emissions related to the NCV of the fuel; boiler load: 200/400 kW; total air ratio = 1.2-1.25; emission limits according to „Feuerungsanlagen-Verordnung“ (FAV, Austria) valid for untreated wood (133 mg/MJ) as well as for straw and other herbaceous fuels (216 mg/MJ) like grains, grasses and miscanthus; emissions related to NCV of fuel

In comparison to relevant Austrian emission limits the NO_x emissions of the testing plant applying optimized air staging are considerably lower (up to 50%).

In Figure 7 the amount of fuel N converted to NO_x versus the N content in the fuel is shown for the different fuels tested. The rate of fuel-bound nitrogen converted to NO_x varies between 26 wt.% for wood chips and 8 wt% for sunflower husk pellets. Figure 7 clearly indicates that the N conversion rate increases with decreasing N content in the fuel. However, although the conversion rate of the fuel-N is lower for fuels with high N content, the total NO_x emissions are higher (see Figure 5).

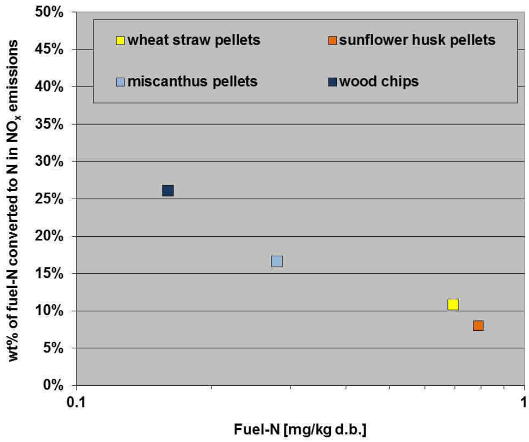

Figure 7: Fuel N converted to NO_x in dependence of N content in the fuel for the fuels tested
Explanations: source of data: [11]

3.3 Results of the CFD simulations performed

The experimental investigations were accompanied and supported by CFD simulations in order to gain more detailed information regarding NO_x formation and to reduce the number of test runs needed. Here one aim was to find a burner configuration which enables an almost complete burnout and therefore low CO emissions as well as to optimise the burner geometry and air staging strategies regarding Low-NO_x operation. In addition, CFD simulations have been performed for wheat straw pellets (high N content) in order to optimise the air staging strategies and to evaluate the influence of the N-content of the fuel on NO_x emissions.

Figure 8 shows the results of the CFD simulations regarding NO_x formation in the combustion chamber (until entry into the 1st heat exchanger duct) for wheat straw pellets (with a N content of the fuel of 0.57 wt.%).

Figure 9 shows the release of the NO_x precursors (NH_3, HCN and NO) during conversion in the gas phase. HCN is mainly released from the tars in the secondary combustion zone 1, so that locally very high HCN concentrations occur. Low HCN concentrations extend into the area of the tertiary air injection and are available in the SCZ for NO reduction. HCN is mainly reduced in the area of the secondary air 2 nozzles, a small part in the area of the secondary air 1 nozzles.

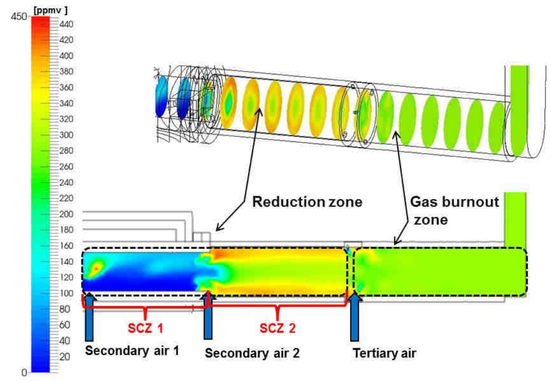

Figure 8: Results from CFD simulations - Iso-surfaces of NO concentrations in the vertical cross-section of the combustion chamber

Explanations: NO_x concentrations as the sum of NO, NO_2 and N_2O concentrations in ppmv; CFD simulation performed at steady state at nominal load (400 kW boiler load); N content of the fuel (wheat straw): 0.57 wt.% d.b.; λ_{SCZ1} = 0.35; λ_{SCZ2} = 0.95; total air ratio = 1.23

In addition, NH_3 released from the fuel bed is mainly reduced in the area of the secondary air 2 nozzles and to some extent in the area of the secondary air 1 nozzles. In the SCZ 2 there are only small traces of NH_3 left. No formation of thermal NO was observed, since the temperature peaks are below 1,400 ° C.

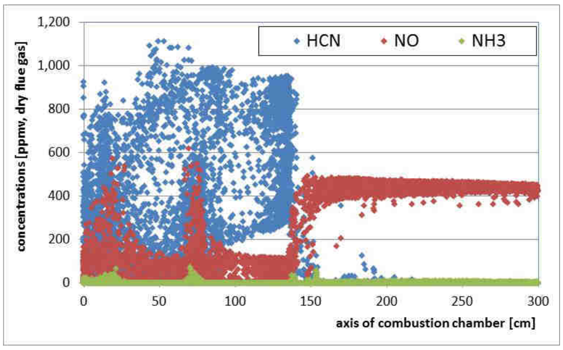

Figure 9: NO, NH_3 and HCN concentrations in the combustion chamber plotted against the axis of the combustion chamber for wheat straw pellets based on CFD simulation results

Explanations: NO, NH_3 and HCN concentrations in [ppmv]; CFD simulation performed at steady state at nominal load (400 kW boiler load); N content of the fuel: 0.57 wt.% d.b.; SA … secondary air; TA … tertiary air; gas released from the fuel bed at 0 cm (x-axis); x-axis … length of the radial combustion chamber

Figure 10 shows the results of the CFD simulations regarding the local TFN/TFN_{in} ratios during conversion in the gas phase. TFN (total fixed nitrogen) is the mass of all N-moles contained in NO, NH_3, NO_2, HCN and N_2O, released from the fuel bed. NO reduction mainly takes place in the area of the secondary air 2 injection.

The simulated NO_x concentration at the inlet to the 1st heat exchanger duct for straw is 183 mg/MJ and for wood chips 86 mg/MJ (based on NO_2 and related to the NCV of the fuel). In comparison, the measured values derived from the test runs with the testing plant with wheat straw pellets (with a comparable N content of 0.69) and wood chips were in the range of 170 mg/MJ for straw and in the range of 73 mg/MJ (based on NO_2 and related to the NCV of the fuel) for wood chips – considering the same air staging as it was applied for the CFD simulations (see also Figure 6). Thus, test run results are in good agreement with the results of the CFD simulations and confirm the practicability of the applied CFD models. These findings concerning NO_x emissions and the conversion of the fuel-bound N of different non-wood biomass fuels are of great relevance for the accurate modelling of Low-NO_x combustion chambers.

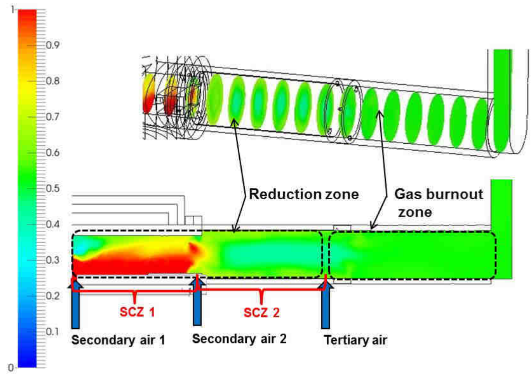

Figure 10: Results from CFD simulations - Iso-surfaces of local TFN/TFN_{in} ratios in the vertical cross-section of the combustion chamber

Explanations: TFN … mass of all N-moles contained in NO, NH_3, NO_2, HCN und N_2O, released from the fuel bed; CFD simulation performed at steady state at nominal load (400 kW boiler load); N content of the fuel: 0.57 wt.% d.b.; λ_{SCZ1} = 0.35; λ_{SCZ2} = 0.95; total air ratio = 1.23

5 SUMMARY AND CONCLUSIONS

In order to investigate the influence of multiple air staging on NO_x emissions, test run series with different biomass fuels (miscanthus, wheat straw, sunflower husk and hardwood) have been performed at a newly developed 400 kW biomass combustion technology specially designed for the application of multiple air staging. Test runs have been performed at stationary load conditions. A good burnout quality could be reached resulting in low average CO 5 mg/MJ (related to the NCV of the fuel) at a total excess air ratio of 1.2-1.3 for all fuels and loads tested.

The clearest and strongest dependence on NO_x emissions in the flue gas was given by the air ratio in the reduction zone of the combustion chamber. This can probably be attributed to the increasing flue gas temperatures with increasing air ratios in the secondary combustion zone resulting in a faster cracking of the N containing tars into NO_x precursors and therefore a faster reduction of NO_x. An optimum can be observed at an air ratio in SCZ 1 between 0.4 and 0.45 and at an air ratio in SCZ 2 between 0.8 and 0.9. The strongest dependence on NO_x emissions in the flue gas is given by the air ratio in SCZ 1 of the combustion chamber.

A second relevant influencing parameter identified is the residence time in the secondary combustion zone. The results show that NO_x emissions at partial load are lower than at full load. This can probably be attributed to the different residence times and temperatures of the flue gas in the reduction zone of the combustion chamber. Thus, increasing residence time decreases NO_x emissions. In comparison to relevant Austrian emission limits the NO_x emissions of the testing plant applying optimized air staging are considerably lower (up to 50%).

The experimental investigations were accompanied and supported by CFD simulations in order to gain more detailed information regarding NO_x formation. The NO_x precursors HCN and NH_3 are released from the fuel bed and, in case of HCN, also in SCZ 1 from the tars, and are mainly reduced at the beginning of SCZ 2. Test run results confirm the results of the CFD simulations and verify the models applied. The findings concerning NO_x emissions are of great relevance for the accurate modeling of Low-NO_x combustion chambers.

It could be show that NO_x reduction by multiple air staging (primary measures) is of relevance for the development and design of Low-NO_x combustion technologies which are tailored to the demands of non-wood fuels particularly with regard to fuels with high N content as NO_x emissions increase with increasing N content in the fuel. Thus, the application of multiple air staging may provide a cost attractive alternative to secondary measures and thereby contributes to a significant widening of the feedstock potential for heat and power production from biomass and the reduction of NO_x, which is a primary contributor to photochemical smog.

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8 LOGO SPACE